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# Electron-Driven Fast Ignition Modeling with Realistic Electron Source

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M. Marinak, D. P. Grote, M. H. Key, D. R. Welch, B. I.  
Cohen, R. P. Town

November 8, 2010

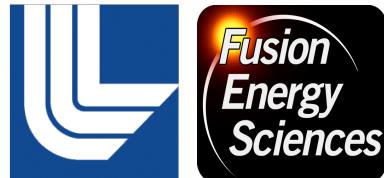
52nd Annual Meeting of the APS Division of Plasma Physics  
Chicago, IL, United States  
November 8, 2010 through November 12, 2010

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# Electron-Driven Fast Ignition Modeling with Realistic Electron Source



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**Lawrence Livermore National Laboratory**

**52<sup>nd</sup> Annual Meeting of the APS Division of Plasma Physics**  
Chicago IL  
**November 8-12, 2010**

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LLNL-CONF-461814

## **Summary: Realistic beam is divergent, gives large ignition energy; need to study focusing schemes like imposed magnetic field**

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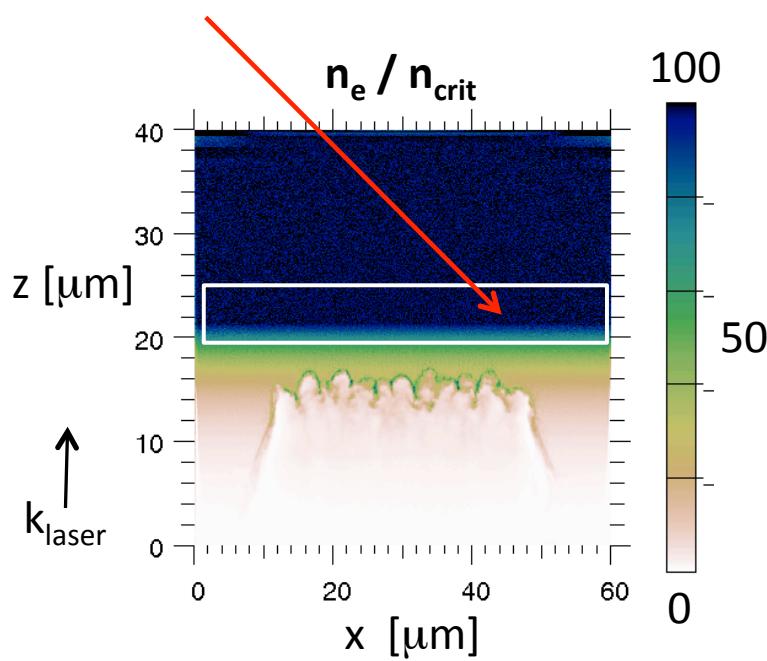
- **Electron source:** from full PIC LPI simulations [A. Kemp, L. Divol]:
  - Energy spectrum: modified two-temperature, ponderomotive intensity scaling.
  - Angle spectrum: highly divergent, avg. polar angle 50 deg.
- **Integrated Zuma-Hydra Modeling:**
  - HYDRA rad-hydro code (M. Marinak et al.) coupled to hybrid-PIC transport code ZUMA (D. Larson).
  - Electron beam excited (no laser) – distribution chosen to replicate full PIC.
- **Realistic beam divergence:** did not ignite even for 352 kJ of electrons - hopeless!
- **Initial axial magnetic field** and realistic divergence:
  - 40 field MG ignites with 44 kJ.
- **Co-authors:** M. Tabak, A. J. Kemp, L. Divol, D. Larson, M. Marinak, D. P. Grote, M. H. Key, D. R. Welch, B. I. Cohen, R. P. J. Town.
- Supprted by LDRDs 08-SI-001 and 11-SI-002.

# We directly compare electrons in full-PIC “white box” with an LSP run with an excited electron beam

## PSC full-PIC run with laser:

- 3D Cartesian, 1  $\mu\text{m}$  wavelength.
- pre-plasma  $n_e \sim \exp[z / 3.5 \mu\text{m}]$ .
- best focus:  $I_{\text{las}}(r) = I_0 \exp[-(r/18.3 \mu\text{m})^8]$
- $I_0 = 1.37 \times 10^{20} \text{ W/cm}^2$ .  $T_{\text{pond}} = 4.63 \text{ MeV}$ .

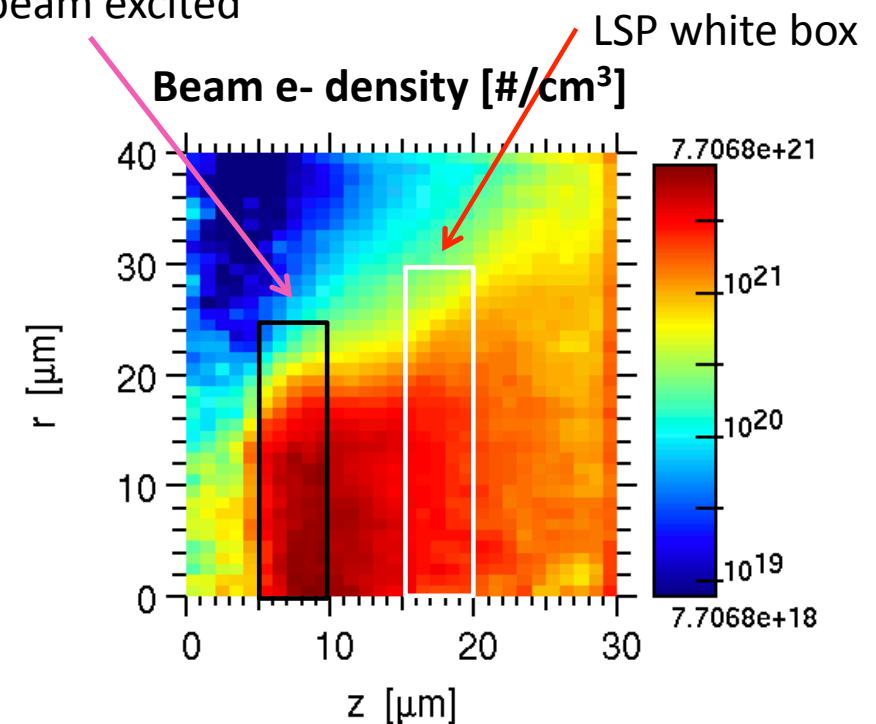
PSC “white box”



## LSP hybrid implicit-PIC run with excited electron beam:

- 10 g/cc, 100 eV, Z=6 carbon.
- RZ Cylindrical.
- No dE/dx or angle scattering (not in PSC run).

e- beam excited



# Beam energetics, and two-temperature energy spectrum

**Energy spectrum: quasi two-temperature,  
scaled ponderomotively**

$$dN / dE = \frac{1}{E} \exp[-E / T_{\text{cold}}] + \frac{b_2}{T_{\text{pond}}} \exp[-E / T_{\text{hot}}]$$

Note asymmetry in the two terms!

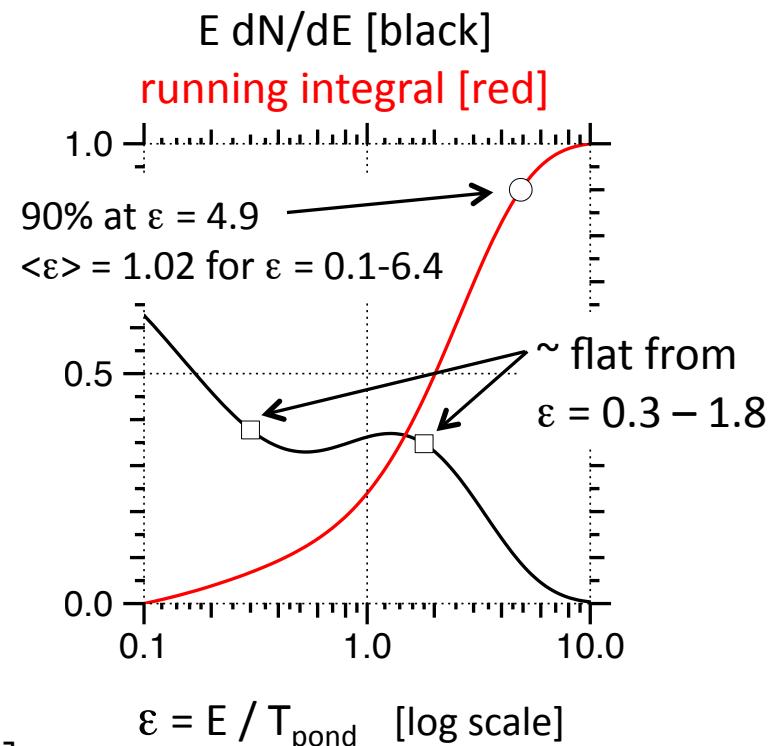
Parameters to fit with full-PIC:

$$T_{\text{cold}} = 0.19 T_{\text{pond}} \quad T_{\text{hot}} = 1.3 T_{\text{pond}} \quad b_2 = 0.82$$

Ponderomotive scaling [Wilks et al., PRL 1992]

$$\frac{T_{\text{pond}}}{m_e c^2} = \left[ 1 + a_0^2 \right]^{1/2} - 1 \sim \sqrt{\frac{I_{\text{las}} \lambda^2}{1.37 \cdot 10^{18} \text{ W cm}^{-2} \mu\text{m}^2}}$$

- LSP beam power = 52% of PSC laser power.
- Total laser absorption is higher ~80-90%, but some is parasitic: expanding plasma, return current, ions, etc.

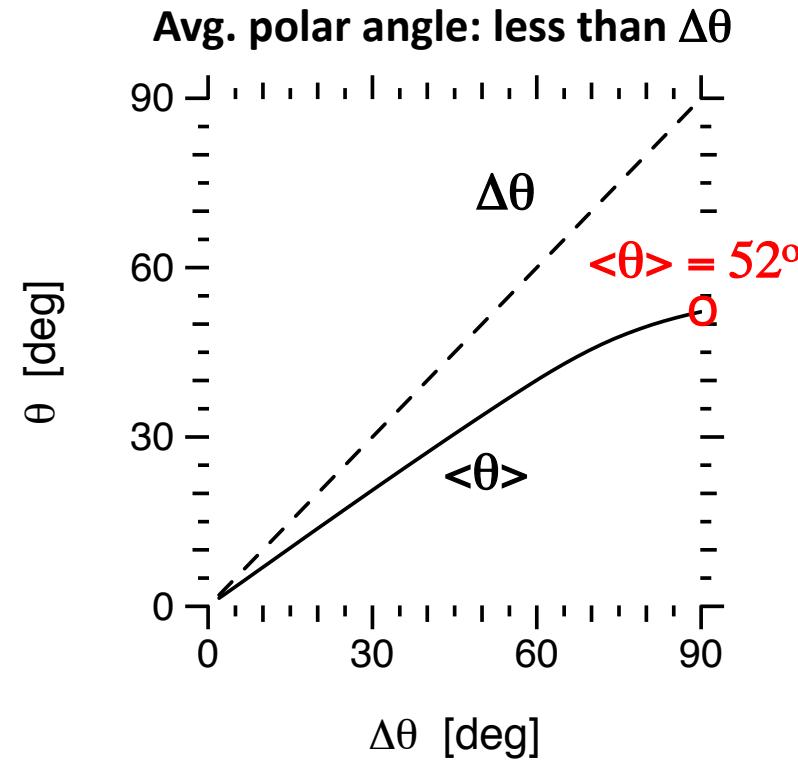
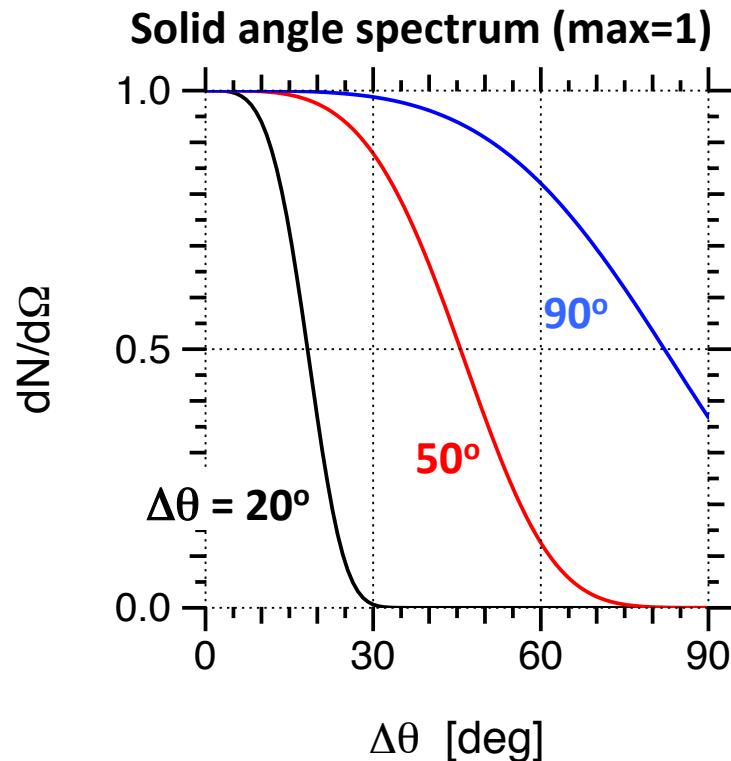
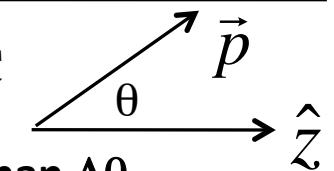


# Beam angle spectrum: super-Gaussian, large divergence

$$\frac{dN}{d\Omega} = \exp \left[ -(\theta / \Delta\theta)^4 \right]$$

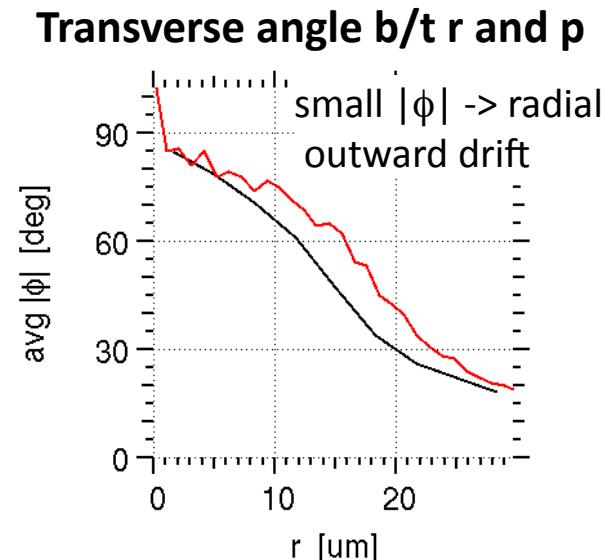
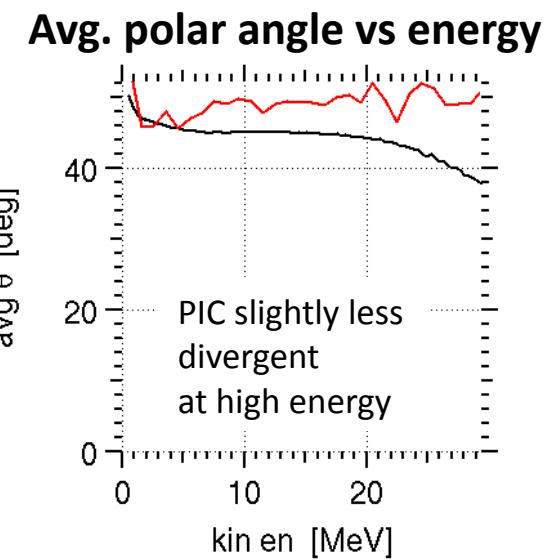
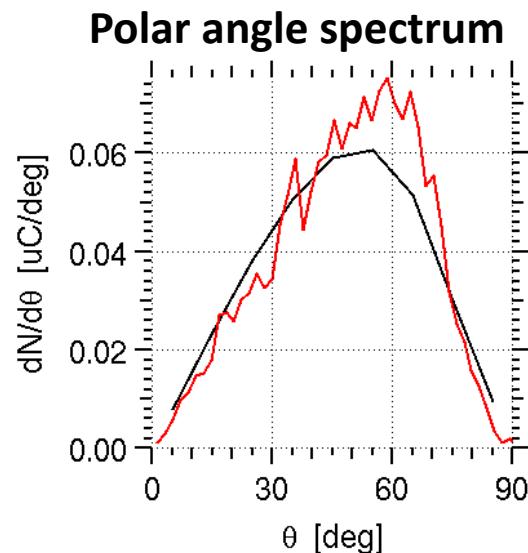
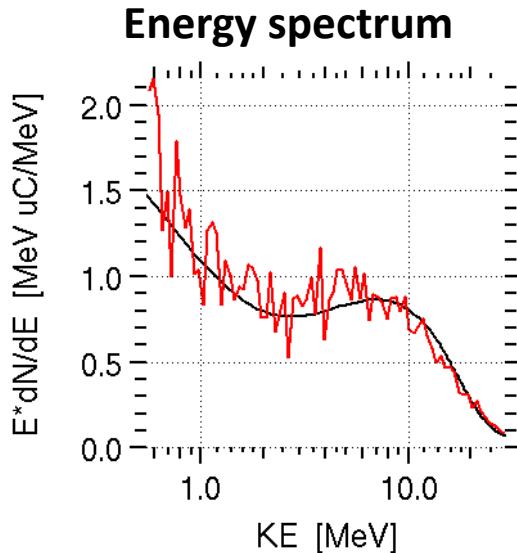
$\theta$  = polar angle

$\Delta\theta = 90^\circ$  matches full-PIC

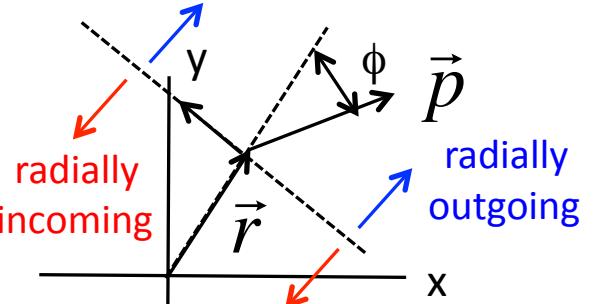


- “Opening angle” is ill-defined: should specify  $\langle \theta \rangle$ ,  $\theta_{rms}$ ,  $\theta$  enclosing 90% of e-, etc.
- Only fwd-going e- excited.

PSC (black) and LSP (red) e- in white boxes are similar enough for transport and design studies



Azimuthal angle in transverse plane:



A. Debayle et al, IFSA 2009  
Proceedings: radial outward drift w/  
Gaussian laser spot;  
azimuthally uniform LSP source  
develops outward drift as it  
propagates.

# Zuma: Hybrid PIC transport code (D. Larson)

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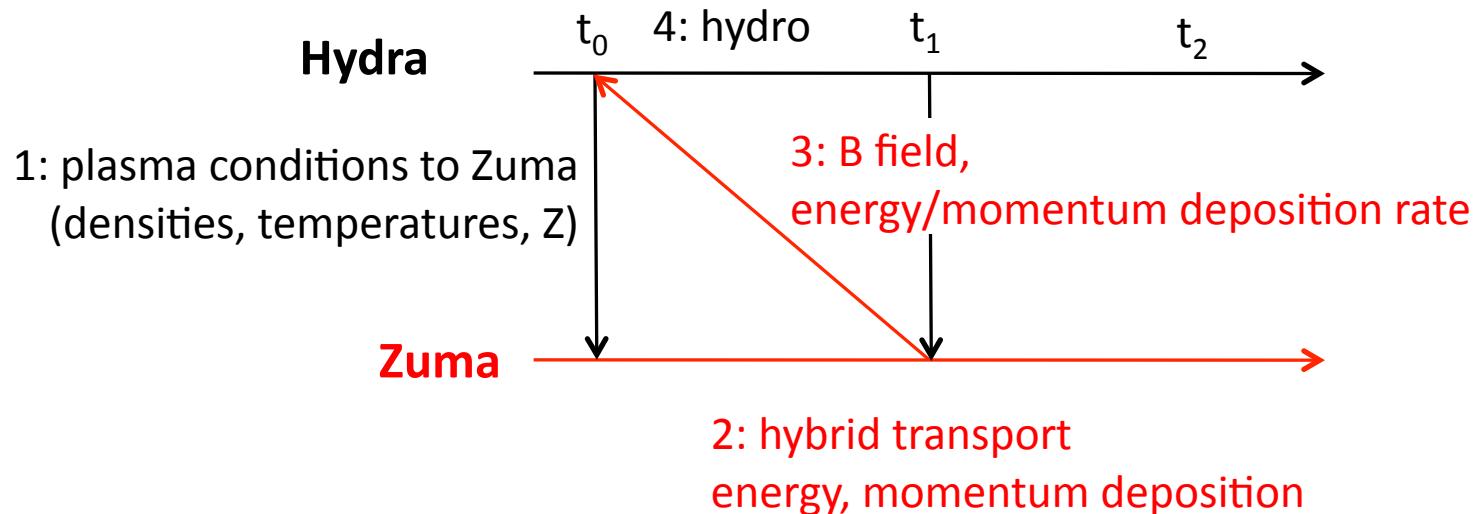
- Fast electrons treated as relativistic PIC particles.
- Field and background dynamics simplified to eliminate light and plasma waves.

## Zuma time step :

- Relativistic push of fast electrons'  $\vec{x}$  and  $\vec{p}$ :  $\vec{F} = -e(\vec{E} + \vec{v} \times \vec{B})$
- Fast e- energy loss (drag) and angular scattering: formulas of Solodov, Betti, Davies
- Collect  $\vec{J}_{\text{fast}}$
- $\vec{J}_{\text{return}} = -\vec{J}_{\text{fast}} + \mu_0^{-1} \nabla \times \vec{B}$  no displacement current
- $\vec{E} = \eta \vec{J}_{\text{return}}$   $\eta$  = resistivity from Lee-More-Desjarlais
- $\vec{J}_{\text{return}} \cdot \vec{E}$  background heating, momentum deposition
- $\frac{\partial \vec{B}}{\partial t} = -\nabla \times \vec{E}$

# Hybrid PIC transport code Zuma coupled to rad-hydro code Hydra

- Both codes run in cylindrical R-Z geometry on fixed Eulerian meshes.

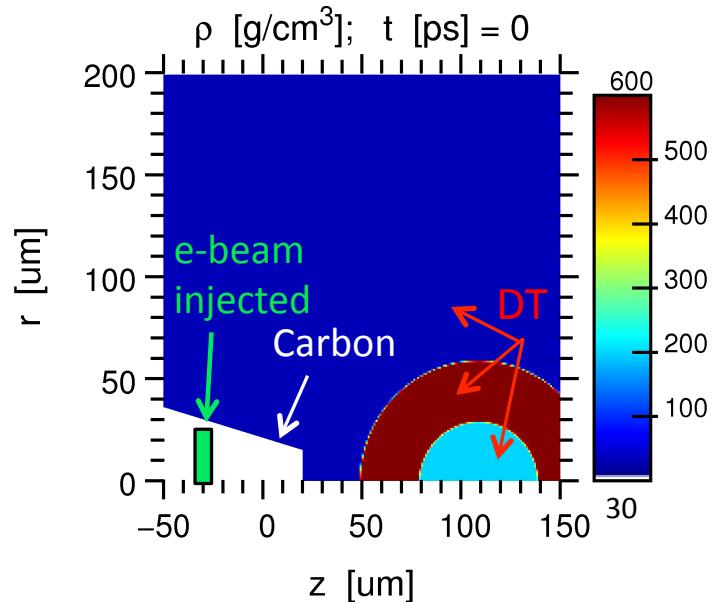


Tues. afternoon posters:

M. Marinak JP9.106: Zuma-Hydra

D. Larson JP9.119: Zuma modeling of wire experiments

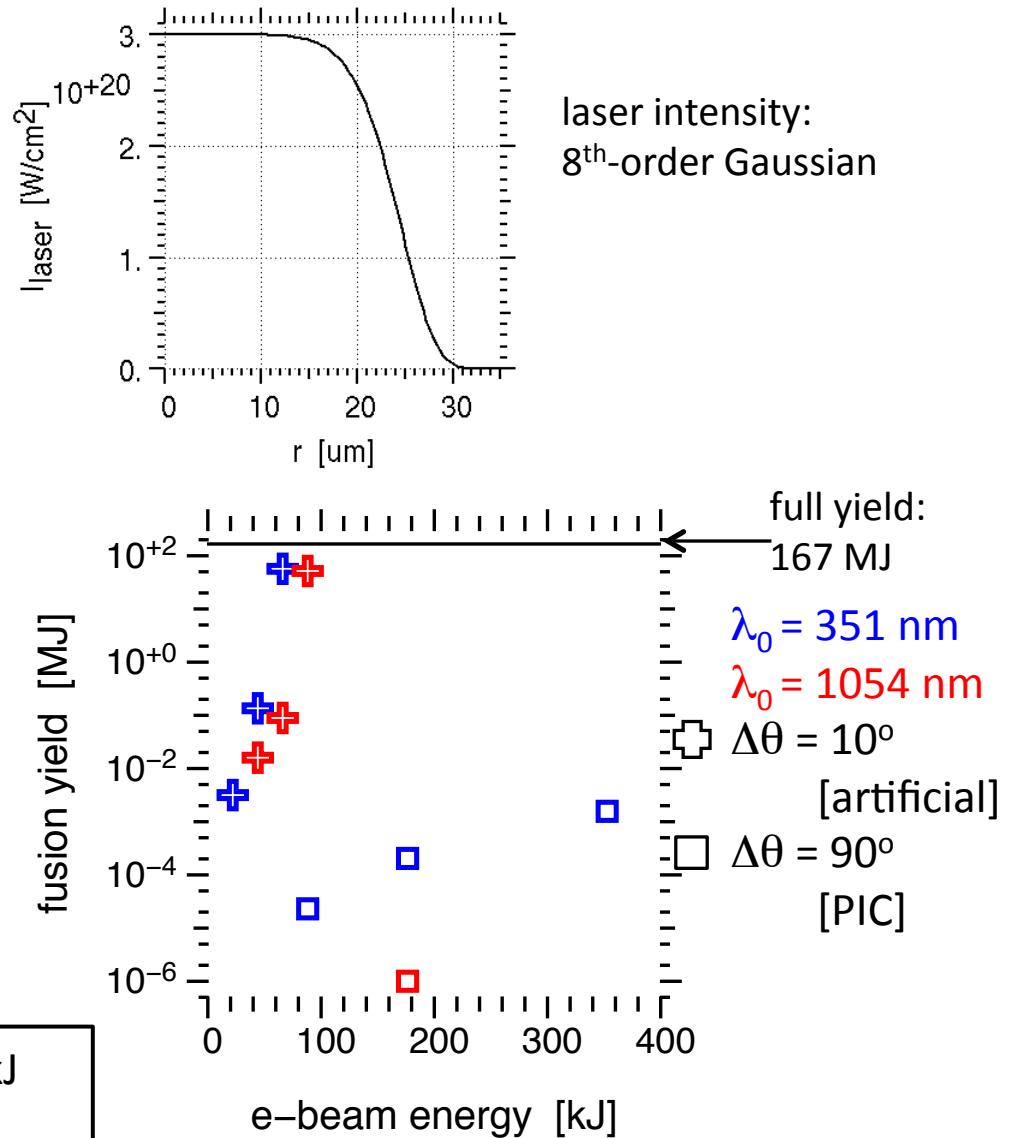
# Zuma-Hydra modeling shows beam divergence has large effect on ignition energy



- 50 μm standoff from beam injection to cone tip, 30 μm from tip to dense fuel
- e-beam intensity = 0.52 \* laser intensity
- 20 ps flattop pulse in time
- Angle spectrum:  $dN/d\Omega = \exp[-(\theta/\Delta\theta)^4]$

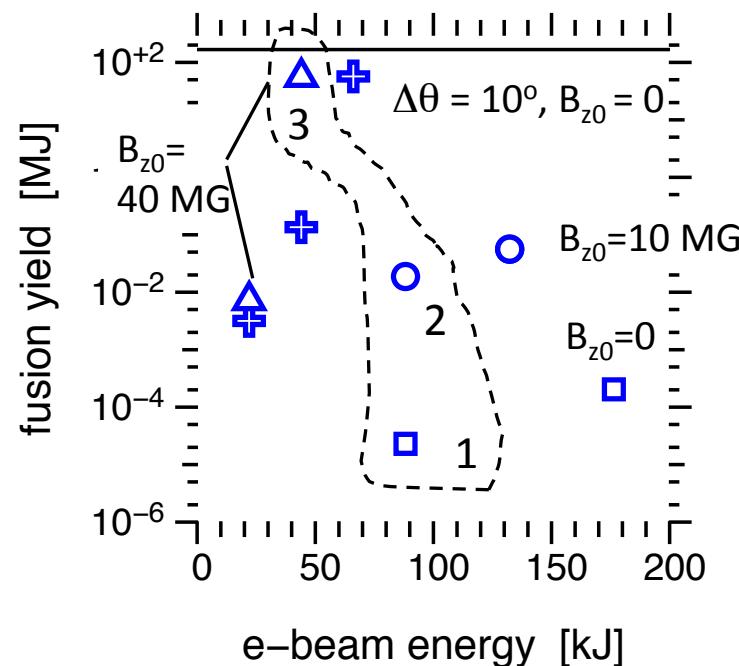
$\Delta\theta = 10^\circ$ : beam ignition energy = (66,88) kJ  
for  $\lambda_0 = (351, 1054)$  nm

$\Delta\theta = 90^\circ$ : > 352 kJ for both  $\lambda_0$ : this is a loser!

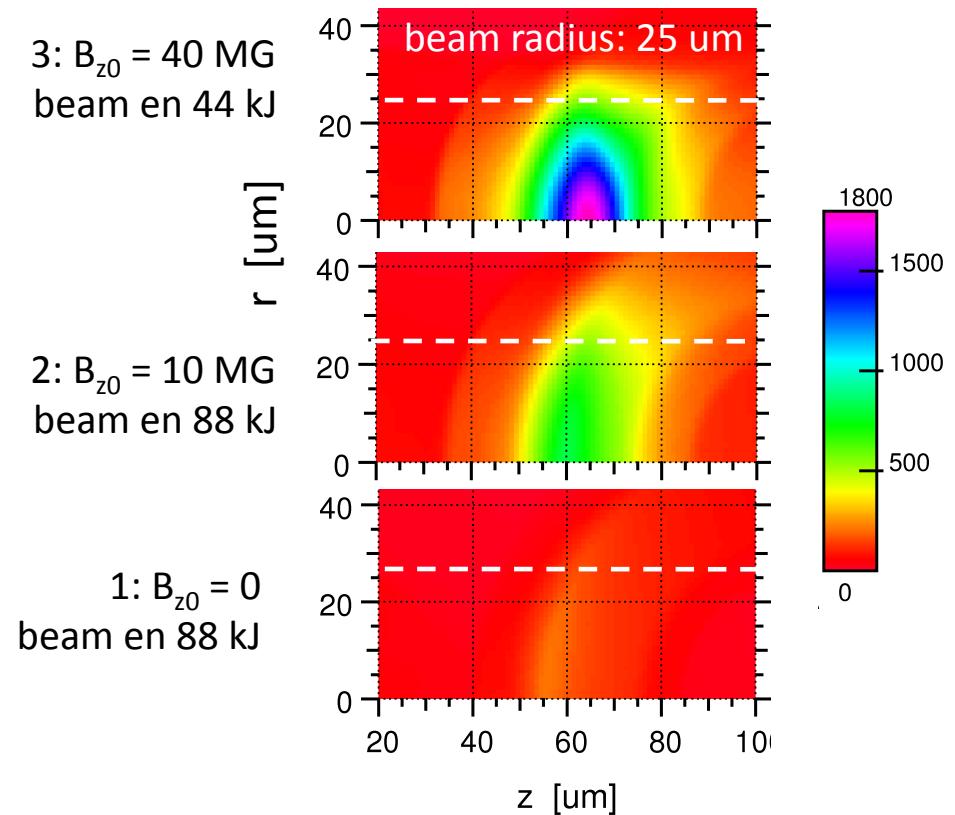


# Initial imposed axial magnetic field substantially reduces ignition energy for beam with realistic divergence

$\lambda_0 = 351 \text{ nm}$ ,  $\Delta\theta = 90^\circ$  [matches PIC]



ion pressure [Gbar],  $t = 20 \text{ ps}$  (end of pulse)



Tues. afternoon posters:  
M. Tabak JP9.105: assembling B-fields

Omega expt's show cylindrical compression  
of 50 kG seed B field to 30-40 MG  
[ J. P. Knauer, APS 2009, Phys. Plasmas 17,  
056318 (2010) ]

Symbol	$B_{z0}$ [MG]	Beam ign energy [kJ]
□	0	>352
○	10	>132
Δ	40	44

# Conclusions

- **Electron source:** full PIC LPI results well replicated by excited e- beam.
  - 52% conversion of laser in e-beam energy
  - Energy spectrum: quasi two-temperature, ponderomotive scaling.
  - Angle spectrum: very divergent supergaussian.
- **Zuma-Hydra integrated ignition studies** with PIC source (not experimentally validated):
  - Realistic divergence doesn't ignite even with 352 kJ of e-beam, or 700 kJ of laser!
  - Imposed axial B field of 40 MG ignites with 44 kJ of e-beam, for 351 nm laser light.
- **Furue work:**
  - Assembling B in implosion.
  - Use of 527 nm or 1054 nm light under study.
  - Recent PIC results of A. Kemp indicate a cooler spectrum than used here after 1-2 ps:  
later this session.

